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Research note

Experimental investigation of bounce phenomenon

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KEYWORDS

Water enter;
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Abstract During the entry of objects into water, several fluid dynamics phenomena, such as air and vapor cavities and jet formation, occur that contribute to the bouncing behavior of the body. In this study, experimental tests are carried out to investigate these effects. In these tests, the consequences of speed and entry angle changes along with different model nose shapes, on bounce phenomenon, are explored. Two models, with different lengths, including hemispherical and conical nose shapes, are also designed, prepared and tested in a test tank, equipped with a high speed movie camera and launching system. As the muzzle velocity increases and the water entry angle decreases, it is observed that the hemispherical nose model has no essential orientation change, while the conical nose model bears an orientation change that is quite large and which may end up in the bounce of the model. This is mainly related to the extent of the separation and jet formation on the nose surface, which is discussed in this paper. A numerical model of the experiment also predicts the same behavior.

1. Introduction

"Water Entry" is mainly involved with the history of air-water interface (that is, change of the original water surface and the generated underwater cavity with time) and with the flow behavior of water and air.

When a body enters water, its behavior comprises a complicated series of events that occur both above and below the original water surface, and which depends on the configuration of the body and conditions of entry. Some details of the body configuration are more important, including shape, size, weight, moment of inertia of the body and also water entry conditions, such as angle of entry [1]. Between the different entry types of a body into water, an oblique entry is very important. At small angles of entry, an oblique entry occurs, known in the literature as bounce or ricochet [2]. Figure 1 depicts different trajectories, followed by the motion of a sphere, and Figure 2 shows the penetration of a projectile into water and its return to air immediately, due to hydrodynamic effects [2]. The kind of trajectory that is followed by the projectile depends on different parameters, such as nose shape, entry angle and velocity.

During oblique water entry, lift and pitching moments are important components of the hydrodynamic force system affecting the trajectory. Pitching moment tends to turn the nose of the body upward (positive) or downward (negative), altering the body angle of attack, and lift is the cause of trajectory change. Regarding the above, the aim of this work is to investigate the effects of parameters, including different nose shapes, as well as water entry and velocity variations, using experimental techniques.

2. Literature review

The first analyses of water impact, experimental as well as theoretical, were related to the study of sea plane landings. Experiments were already being performed in the early days of aviation, [3]. Sottorf [4] studied the load/resistance relation, with regard to pressure distribution, for different planing surfaces.

Besides planing experiments, drop tests have been established for bow-stem slamming. In these setups, a test section, such as a wedge, is dropped from various heights toward the water surface. Chuang [5] investigated experimentally wedge

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Figure 1: Four types of trajectory identified by Richardson [2]. (a) Definite ricochet with the angle of exit somewhat less than the angle of entry; (b) break-surface often followed shortly by re-entry; (c) flattening-out and continuing on a straight path for a certain distance followed by diving; and (d) continuing straight ahead, then diving.

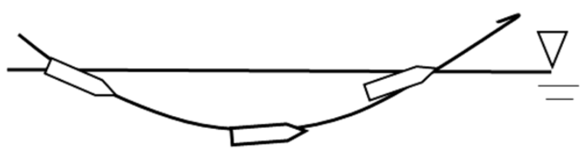


Figure 2: Penetration and return of a body due to hydrodynamic effects [2].

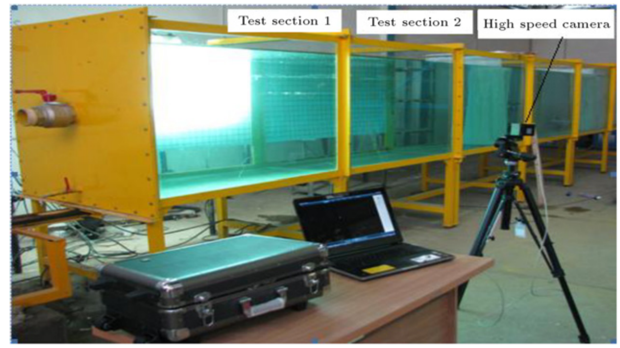


Figure 3: View of experimental set up.

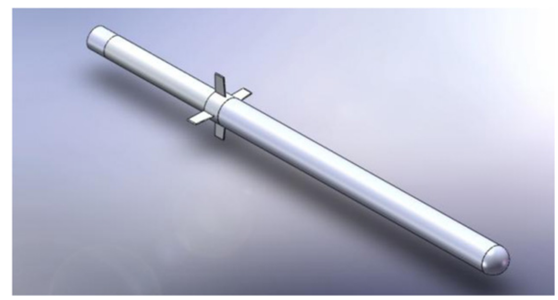


Figure 4: Spherical nose model.

shaped and flat-bottomed sections. The experiment involved pressure measurements and, for small dead rise angles, cushioning was observed. It was reported that the entrapment of air between the body and the water surface decreases the magnitude of hydrodynamic impact. Drop tests with large scale specimens were performed by Hayman et al. [6]. This experiment also involved flexible structures and measurement of the elastic structure response. Drop tests were performed with the objective of validating theoretical models for impact pressure distribution by Zhao et al. [7]. An extensive analysis of two-dimensional hull-water impact and the impact-planing analogy is presented in [8]. Battley and Stenius [9] carried out drop tests with controlled velocities. This study was performed on a flexible sandwich structure, and pressure, impact force and structure responses were measured.

It is noteworthy that Faltinsen et al. [10] performed an extended study on several aspects of water entry, particularly on impact problems such as wet deck slamming, green water and bow-stem slamming, tank sloshing, and many other subjects in this context.

Using an experimental approach, Yettou et al. [11] studied the pressure distribution on various wedges during their vertical penetration into water. They provided the description of an elaborate experimental set-up, designed to test the hydrodynamics of the water-entry process of a two-dimensional V-shaped wedge.

Cole et al. investigated experimentally the high-speed water entry of full scale and Froude scale models of vehicles [12]. The main objective was to measure pressure in the air pocket entrainment over vehicles, in order to determine the force required to eject a vehicle.

Experimental investigations continued when New et al. [13] investigated the impact of prismatic bodies with various fore-sections. The bodies were launched using a compressed air chamber and a solenoid valve, capable of simulating a range of impact angles. The body accelerations were measured using an accelerometer and both the water splash and air pocket entrainment were recorded using high-speed video and photography.

In this way, Lin and Shieh [14] and Shi and Kume [15] provided experimental data on water pressure and the acceleration of bodies with round cylindrical shapes.

Another series of work in recent decades has taken place to collect, systematically analyze, and quantify experimental data on the complex three-dimensional behavior of an instrumented cylinder during freefall for military aims [16–18]. To the best of the author's knowledge, according to open literature, there are few references about oblique water entry problems and jet formation around the body, particularly in accelerated motion. Therefore, an experimental set-up was devised and a series of experiments performed that are explained in the following, accompanied by a discussion of results and comparison with a flow field simulation.

3. The experimental setup

To perform water entry tests, a water tank is designed and installed. Canal dimensions are such that the effect of walls on the flow field is small, i.e. a cross section of 1.2 by 1.2 m and 9 m in length. A launching system provides different model velocities by variation of the gun powder. Figure 3 depicts a typical test set-up, including a high speed camera (up to 36,000 frame/s), a computer for image processing, a test tank and a lighting system.

Two different models were considered, one with a hemispherical nose shape and the other with a conical head. These models show clearly the effect of nose shape on bouncing the model from the water surface. At first, the hemispherical nose model, with a velocity of 30 m/s and an entry angle of 30°, with respect to the water surface, was launched. Afterwards, effects of velocity and entry angle variations were investigated by changing the velocity up to 60 m/s and entry angles lower than 10°. In the following, the effects of nose shape, velocity and entry angle on the model trajectory are presented.

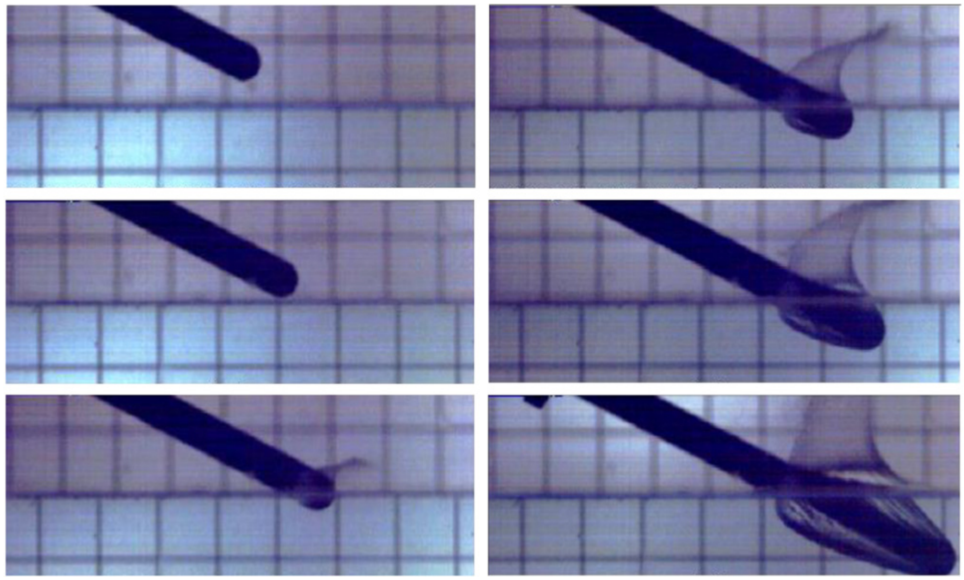


Figure 5: Water entry of the model with entrance velocity and entry angle 29.15 m/s and 25.157°, respectively at different times.

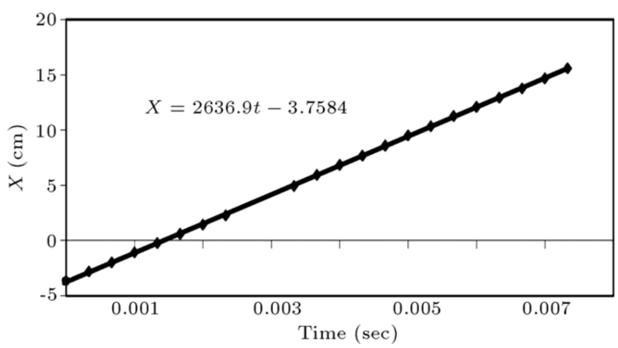


Figure 6: X-position of the spherical nose model versus time with entrance velocity and entry angle 29.15 m/s and 25.157°, respectively.

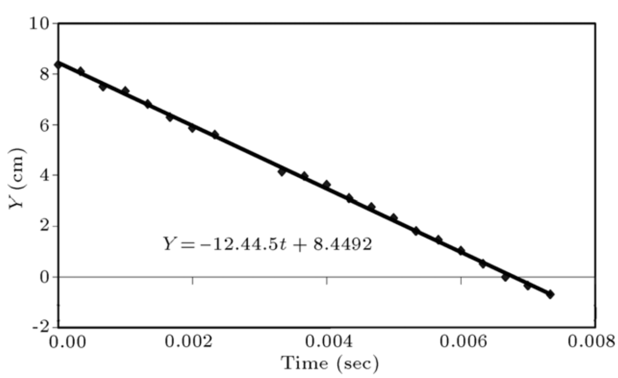


Figure 7: Y-position of the spherical nose model versus time with entrance velocity and entry angle 29.15 m/s and 25.157°, respectively.

4. Impact problem of hemispherical nose model

A model, including a spherical nose and cylindrical body, is considered. Figure 4 shows the model and its cruciform fins, which are solely employed for flight stabilization. The mass, center of gravity, diameter and length of the model are 232 g, 22 cm from the nose, 26 mm and 48 cm, respectively. Some characteristics of the body have been summarized in Table 1.

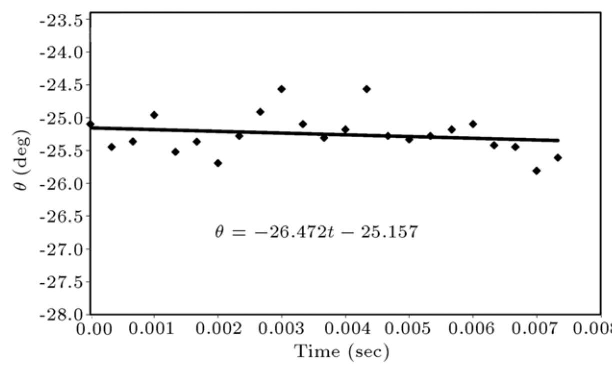


Figure 8: Orientation of the spherical nose model versus time with entrance velocity and entry angle 29.15 m/s and 25.157°, respectively.

Table 1: Some characteristics of the body.

Mass	Length	Diameter	Number of fins	Center of mass
232 g	480 mm	26 mm	4	220 mm from nose

In this study, high speed photography over one test section, shown in Figure 3, is carried out. Figure 5 depicts a series of photographs taken using a high speed camera, with 15,000 frame/s. Development of a jet formation around the body and particularly on the underside region can be seen in these figures.

4.1. Data processing

Different parameters are derived from the pictures taken by the high speed camera. These quantities consist of the body position in horizontal and vertical directions (X, Y) and its orientation. After processing the data, using local differences, velocity components at various times and subsequently acceleration and total drag force can also be calculated.

Figures 6–8 depict the position and orientation of the body versus time. Location changes in both directions of X and Y are evaluated using linear curve fittings and shown in these figures. As seen from these curve fittings, according to Figures 6–8,

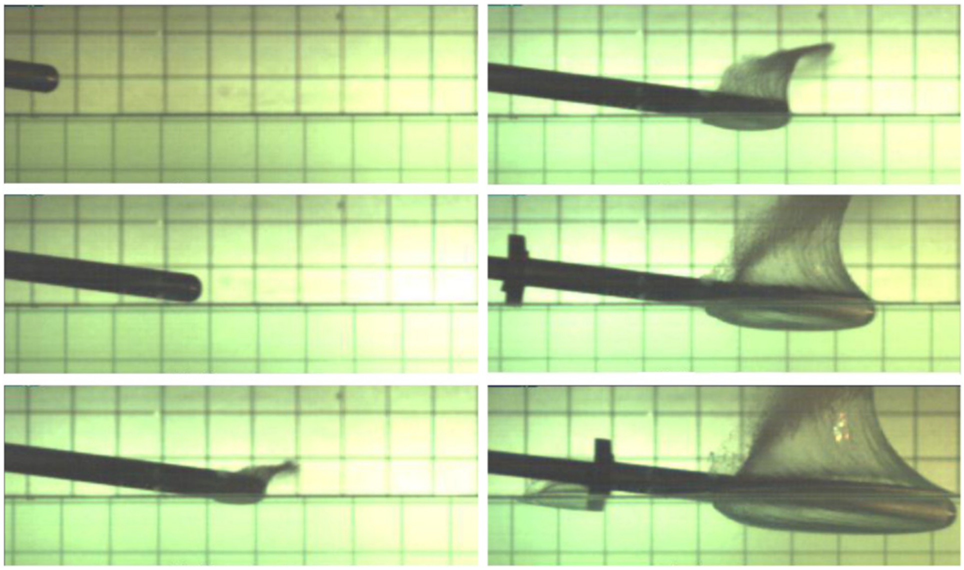


Figure 9: Water entry of the model with entrance at velocity and entry angle 63.2 m/s and 7.5°, respectively, at different times.

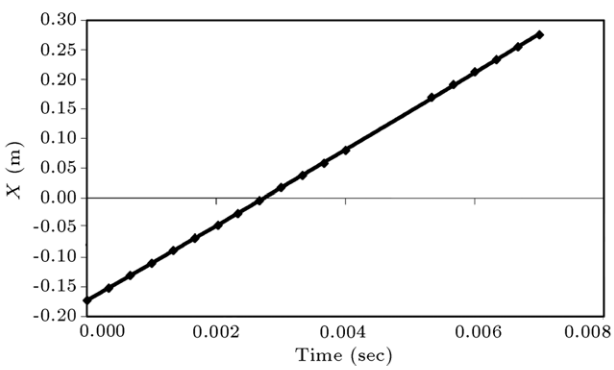


Figure 10: X-position of the spherical nose model with entrance velocity and entry angle 63.2 m/s and 7.5°, respectively.

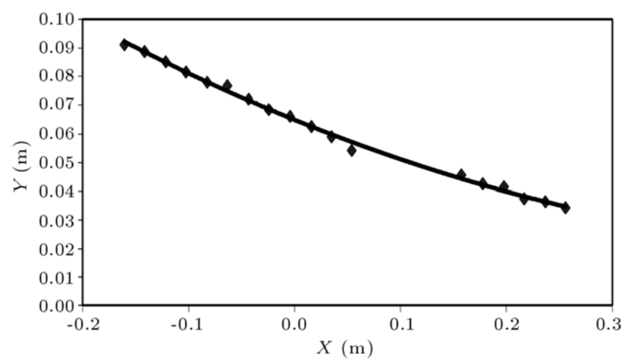


Figure 12: Trajectory of the spherical nose model with entrance velocity and entry angle 63.2 m/s and 7.5°, respectively.

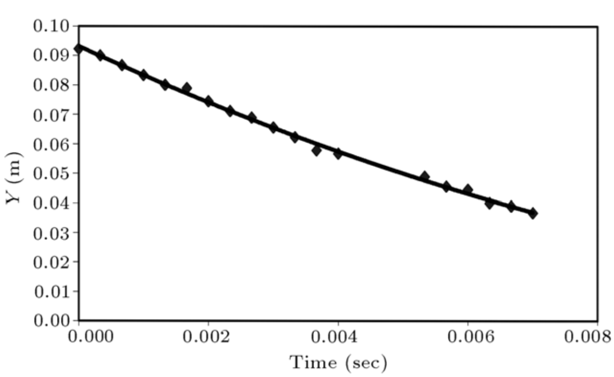


Figure 11: Y-position of the spherical nose model with entrance velocity and entry angle 63.2 m/s and 7.5°, respectively.

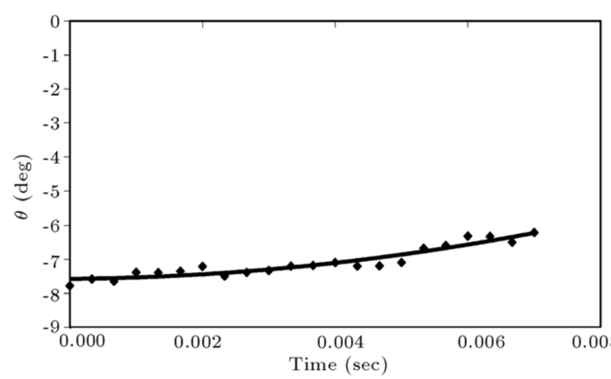


Figure 13: Orientation of the spherical nose model with entrance velocity and entry angle 63.2 m/s and 7.5°, respectively.

maximum velocity is 29.15 m/s and the entry angle is 25.157°. It seems that the velocity and orientation changes of the body at different instants of water entry are not considerable.

4.2. Effects of velocity and entry angle changes

Effects of different velocity and entry angles on the trajectory of the model are investigated in this section. These changes are implemented by increasing the gun powder of the launching system and lowering the entry angle. In the following, some pictures taken, using a high speed camera, are shown in Figure 9. As seen, compared to the previous test, by using suitable lights around the test section, better quality pictures have been taken.

Figures 10–12 depict location changes and the trajectory of the body versus time, respectively. As seen from Figures 13

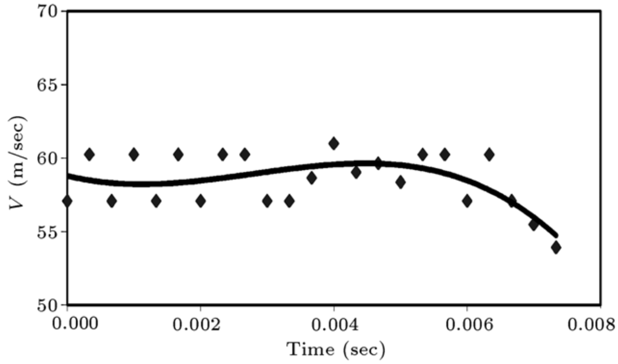


Figure 14: Velocity magnitude versus time of the spherical nose model with entrance velocity and entry angle 63.2 m/s and 7.5°, respectively.

Figure 15: Model with conical nose.

and 14, the entry angle is 7.5° and maximum velocity is 63.2 m/s. Although the direction change, in this case (1.4° from Figure 13), is more than in the previous test (Figure 8), overall, it is not considerable enough to warrant effects such as ricochet or bounce. It should be mentioned that this increase in direction change, in the present case, is expected as the water entry velocity is higher in the present case.

Table 2: Some characteristics of conical nose model.

Mass	Length	Diameter	Number of fins	Center of mass
155.3 g	163.0 mm	15.5 mm	4	60 mm from nose

As can be seen from Figures 13 and 14, velocity and entry angle decrease with time. However, there is no sensible effect on the orientation change of the model. It seems that the spherical nose of this model has no remarkable effect on the orientation change at different instants of motion, even with increased velocity.

5. Impact problem of the conical nose model

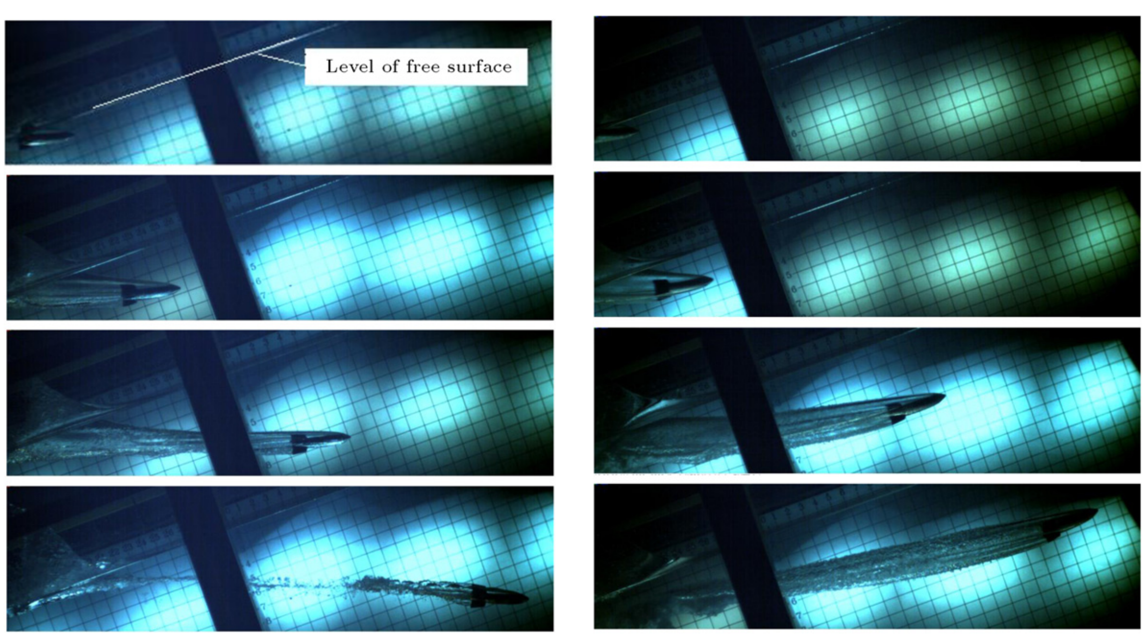
Figure 15 shows the model with a conical nose. The figure also depicts cruciform fins, which are solely employed for flight stabilization. Stabilizers are sized to provide the calm and stable motion of the model. Some characteristics of the body have been summarized in Table 2.

The model is launched at a safe distance from the water surface to prevent interference of remained gases from the launching system on the original water entry flow field.

In this water entry study, two different muzzle velocities (11.4 m/s and 31.5 m/s) along with an entry angle of approximately 17° are used. High speed photography, over two test sections, is carried out. Figure 16 depicts a series of photographs taken with a high speed camera using 5000 frame/s for two different muzzle velocities. As can be seen, by increasing muzzle velocity, the inclination change of the body during water entry is thoroughly increased. In the following, this issue is investigated in detail.

5.1. Data processing

Similar parameters, such as those of the previous test, are derived from the pictures taken by high speed camera.



(a) Entrance angle 17.3° and entrance velocity 11.4 m/s.

(b) Entrance angle 16.8° and entrance velocity 31.5 m/s.

Figure 16: Impact of conical nose model.

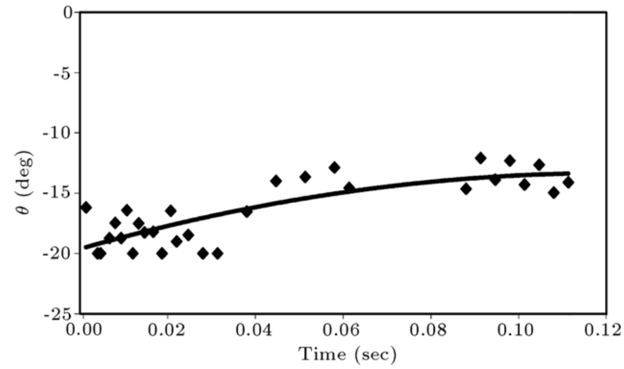


Figure 17: Orientation of the conical nose model versus time with entrance velocity, 11.4 m/s.

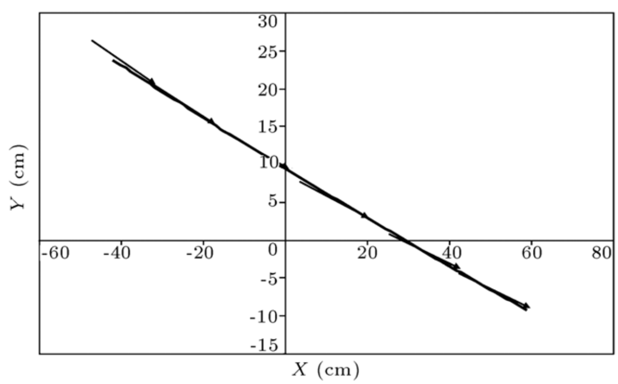


Figure 18: Trajectory of the conical nose model with entrance velocity, 11.4 m/s.

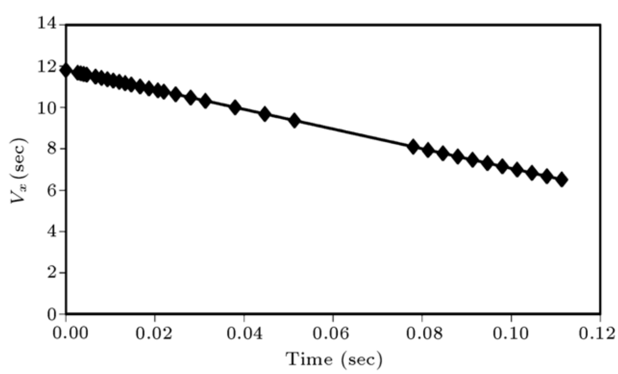


Figure 19: Velocity magnitude of the conical nose model versus time with entrance velocity, 11.4 m/s.

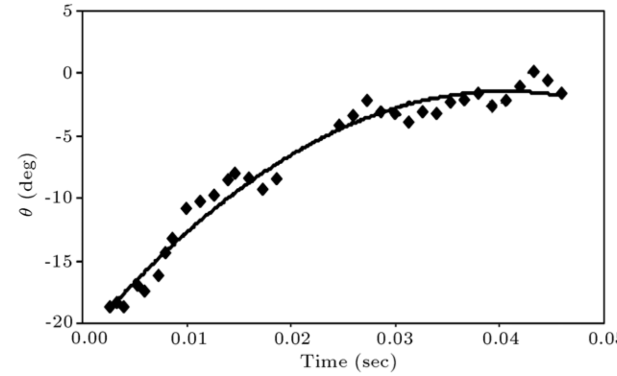


Figure 20: Orientation of the conical nose model versus time with entrance velocity, 31.5 m/s.

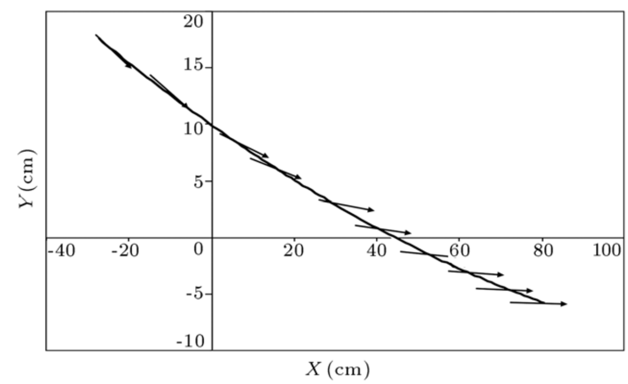


Figure 21: Trajectory of the conical nose model with entrance velocity, 31.5 m/s.

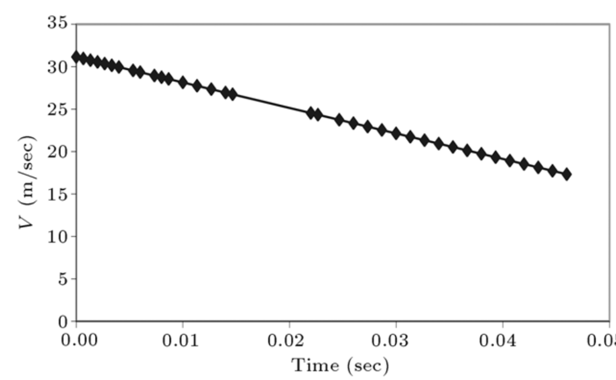


Figure 22: Velocity magnitude of the conical nose model versus time with entrance velocity, 31.5 m/s.

These quantities consist of body position and its direction. After processing the data, using local differences, velocity components at various times and trajectories can also be calculated. In the following, results for two different muzzle velocities of 14 and 31.5 m/s are presented.

Figure 17 depicts the orientation of the body versus time for a muzzle velocity of 11.4 m/s. The trajectory of the body in the X–Y plane, along with its orientation, is shown in Figure 16. As seen in Figures 17 and 18, the total direction change of the body is about 7°. Figure 19 depicts velocity magnitude versus time. As time passes and the body enters into the water, the velocity is decreased by almost a factor of 55%.

In the second case, the velocity is approximately tripled, increasing the charge of the launching system. Figure 20 depicts the orientation of the body versus time for a muzzle velocity of 33.4 m/s. The trajectory of the body in the X–Y plane, along with its orientation, is shown in Figure 19. As seen in Figure 21, there is a remarkable orientation change of more than 15°. This orientation change can also be noticed qualitatively from Figure 15. Figure 22 shows the velocity magnitude versus time. As time passes and the body enters into the water, the velocity is decreased by almost a factor of 50%, as before, which is in agreement with the physics of the problem.

Comparison of the previous results indicate that the difference in orientation change of the conical nose model with entrance velocity, i.e. almost 8°, is more pronounced than that of the spherical nose model, i.e. at most 2°. This is mainly

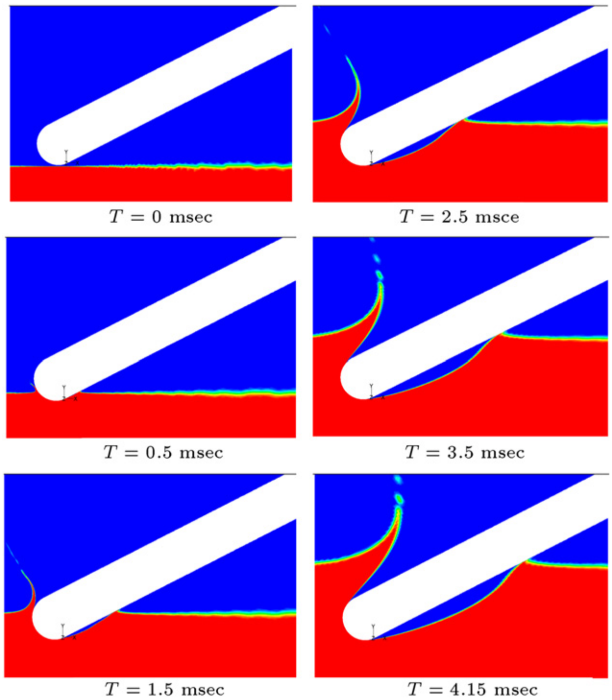


Figure 23: Flow simulation of the test model shown in Figure 4.

caused by the occurrence of underside flow separation at early instants of flow entry. This flow separation, accompanied by jet formation, can be clearly seen in Figure 7 for the spherical nose model, which generates low pressure at the bottom side of the nose and consequently a smaller normal force. The flow does not separate from the conical nose to the same extent as from the spherical nose (Figure 16) and, therefore, a larger than normal force is produced on the conical nose.

The above argument explains qualitatively different direction changes for different nose shapes and the higher tendency of the conical nose shape for bounce from the water surface. It seems that a careful modeling and analysis of water entrance phenomenon is necessary. To show that flow separation and jet formation for spherical noses are important agents for reducing normal force and bounce tendency, a preliminary flow simulation of the experiment shown in Figure 5 is carried out and the results are shown here. Although the details of the numerical study are not discussed for the sake of briefness, the results shown in Figure 23 depict flow separation and jet formation.

6. Conclusion

In this study, effects of speed and entry angle changes in bounce phenomenon are studied for two different nose shapes. It is shown that the orientation change of the conical nose model is much larger than that in the case of a spherical nose. It seems that nose shape has a central role to play in bounce occurrence, while velocity and entry angle changes have some effects, albeit to a lower extent. The main reason, in this regard, is the larger separation region and enhanced jet formation for the spherical nose model compared with that of conical nose model. A larger separation region, accompanied by higher momentum jets, enhances air bubble entrainment on the upper part of the conical model, to a larger extent. These aspects will be studied more thoroughly in future investigations.

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